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 RECIPROCAL STRIPLINE FERRITE PHASE SHIFTER
 HAVING A FOLDED CENTER CONDUCTOR
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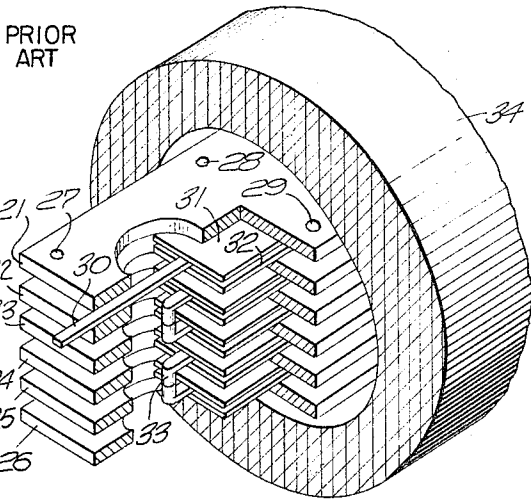


FIG. 1

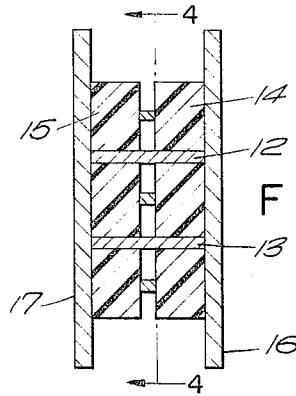


FIG. 5

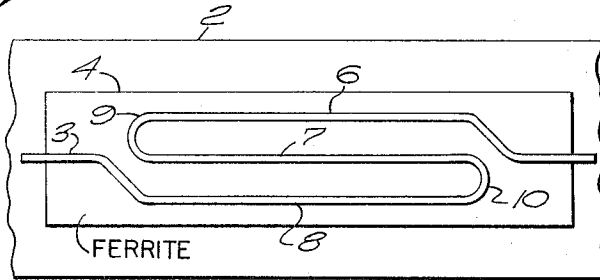


FIG. 3

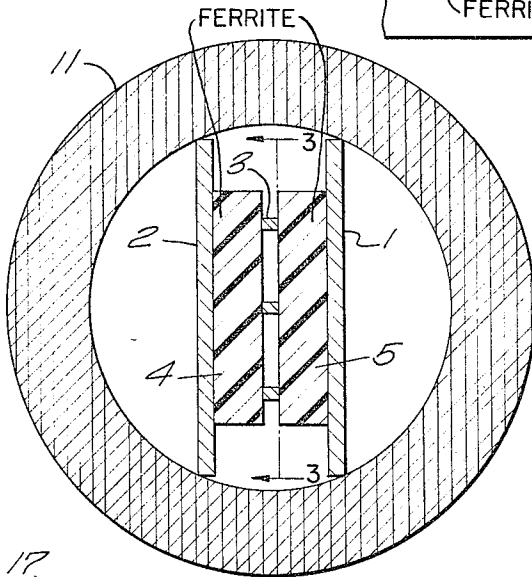


FIG. 2

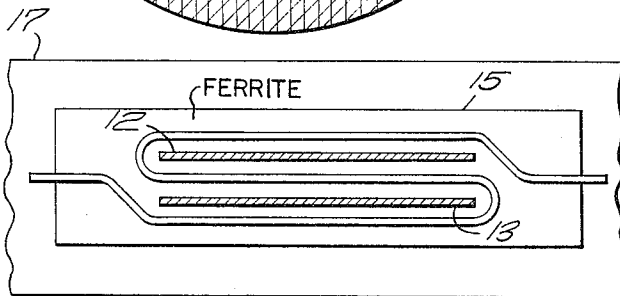


FIG. 4

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1

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RECIPROCAL STRIPLINE FERRITE PHASE SHIFTER HAVING A FOLDED CENTER CONDUCTOR

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This invention relates to apparatus for shifting the phase of electromagnetic wave energy and more particularly pertains to a variable phase shifter, employing a ferrite wave transmission medium, for use in the microwave region of the electromagnetic spectrum.

While several varieties of controllable phase shifters utilizing ferrites are available for use at microwave frequencies, such devices generally operate over a narrow region of frequencies, and are excessively bulky or have a poor figure of merit. Figure of merit denotes the phase shift per decibel of loss. The invention provides a compact controllable ferrite phase shifter that is reciprocal in operation and has relatively low loss over a wide band in the microwave region.

A compact ferrite phase shifter has been described by C. M. Johnson in the January 1959 IRE Transactions on Microwave Theory and Techniques, vol. 7, at pages 28 to 31, upon which the present invention is an improvement. The phase shifter of Johnson employs strip transmission line in which wave propagation occurs in a ferrite transmission medium that is influenced by a magnetic field placing the operating region of the ferrite above resonance. Johnson's device is constructed of a number of superposed segments of ferrite loaded strip transmission line in which the ground plane plates of the segments are electrically connected together by shorting screws and the center conductor of each intermediate segment is connected at one end to the center conductor of the immediately superjacent strip line segment and at the other end is connected to the center conductor of the immediately subjacent strip line segment. Because of the construction employed by Johnson an impedance matching problem arises between successive layers of ferrite that results in a poorly matched device for some values of phase shift. Further, in Johnson's construction, the ground plates shield the ferrite where it is desired to modulate the magnetic field at high modulation frequencies.

The invention is a controllable phase shifting device utilizing a strip transmission line employing a ferrite wave propagation medium. In the invention, the center conductor of the strip transmission line is folded between a pair of ferrite slabs interposed between the common ground planes, and the device has apparatus for establishing a longitudinal magnetic field of an intensity placing the operating region of the ferrite above or below resonance.

The principal object of the invention is to obtain an improvement upon the performance of Johnson's phase shifter from a simpler and more compact device.

The invention, both as to its construction and manner of operation, can be apprehended by a consideration of the following exposition which is intended to be studied in conjunction with the accompanying drawing in which:

FIG. 1 depicts a prior art strip transmission line phase shifter employing a ferrite wave propagation medium;

FIG. 2 is a cross-sectional view of a ferrite phase shifter constructed in accordance with the invention;

FIG. 3 illustrates the folded center conductor of the strip line employed in the invention;

FIG. 4 depicts in plan view an embodiment of the invention employing vanes to prevent electrical interaction between adjacent segments of the folded center conductor; and

2

FIG. 5 is a cross-sectional view of the folded center conductor and the interposed vanes.

FIG. 1 depicts a folded strip line phase shifter of the type described by Johnson in the IRE Transactions, cited supra. Johnson's phase shifter comprises a stack of brass plates 21 to 26 that are electrically coupled together by shorting screws 27, 28, 29 extending through the stack. The brass plates are the ground planes of a segmented strip transmission line. Between each pair of brass plates extends the center conductor 30 of the segmented strip line. The center conductor is sandwiched between a pair of ferrite slabs as at 31 and 32. The ends of the center conductor protrude from between the ferrite slabs and one end is connected to the center conductor of the immediately superjacent strip line segment, as at 33, whereas the other end is connected to the center conductor of the immediately subjacent strip line segment. Holes are provided in the brass plates permitting the center conductor segments to be joined without shorting to the ground planes. The center conductor 30 is thus folded back and forth between the brass ground planes and wave transmission occurs through the ferrite medium except at the protruding ends of the center conductor where wave propagation occurs through air.

The structure of FIG. 1 is operated in a longitudinal magnetic field established by a cylindrical solenoid 34 that surrounds the structure. The magnetic field is of such intensity that it places the operating region of the ferrite above resonance. The device may employ a transverse magnetic field rather than a longitudinal field but Johnson reports that the phase shift obtained from a transverse field is considerably less than the phase shift obtained from a longitudinal field of the same intensity.

Because the ends of the center conductor 30 protrude from the ferrite plates into air, the wave propagation medium is alternately ferrite and air. The transitions between ferrite and air, through which the waves propagate, presents impedance mismatches which give rise to reflections of the wave energy and increase the loss of the line. In the Johnson construction, the air dielectric can be replaced by other dielectric materials, if desired. The impedance mismatch of each ferrite and dielectric transition need not necessarily be poor in Johnson's device, but the fact that there are so many transitions gives significance to event a small mismatch. As the phase shift of Johnson's device is changed, the effect of the mismatch at the transitions add at some values of phase shift and cancel at other phase shift values. That characteristic of Johnson's construction is highly deleterious to performance and limits the usefulness of the FIG. 1 device.

Where the current supplied to the solenoid has an A.C. modulation component for causing a phase swing of the energy transmitted through the phase shifter, the ground plane plates act as shields for the ferrite slabs at high modulation frequencies. The shielding effect is due to the eddy currents induced in the ground plane plates by the changing magnetic field of the solenoid.

FIG. 2 is a cross section of a phase shifter constructed in accordance with the invention. A pair of parallel, spaced, conductive plates 1 and 2 act as the ground planes of a strip transmission line having its center conductor 3 disposed between a pair of ferrite slabs 4 and 5. As best shown in FIG. 3, the center conductor is folded to provide three parallel segments 6, 7, 8 of approximately equal length joined by 180° loops 9 and 10. The strip line structure is surrounded by a solenoid 11 which establishes a longitudinal magnetic field of an intensity causing the ferrite, preferably, to operate in the region below resonance. By altering the intensity of the magnetic field, the velocity of wave propagation in the ferrite slabs is altered and thereby the phase of the propagating wave

energy is controlled. The phase shift due to the ferrite is reciprocal in nature inasmuch as the phase shift is not affected by the direction of the longitudinal magnetic field. The phase shift along segment 6 of the center conductor is added to the phase shift along segments 7 and 8 even though the direction of the longitudinal magnetic field with respect to the direction of wave propagation through the device is in the same direction for segments 6 and 8 and in the reverse direction for segment 7. Impedance matching difficulties are considerably diminished because the 180° loops 9, 10, as well as the linear segments of the center conductor are disposed between the ferrite slabs so that wave propagation occurs in a medium having a uniform dielectric constant.

The length of the center conductor segments depends upon the amount of phase shift to be furnished by the device. The number of folds of the center conductor can be increased where the length of the linear segments must be kept within specified limits or the number of folds can be diminished where a longer device can be tolerated and increased driving power for the solenoid is available.

The spacing between the parallel linear segments of the center conductor may be reduced considerably where shorting vanes or posts are interposed between the segments to prevent electrical interaction between adjacent line segments. The construction of a phase shifter utilizing such shorting vanes is depicted in FIGS. 4 and 5. As can be seen, the construction is similar to that shown in FIGS. 2 and 3 except that electrically conductive vanes 12 and 13 are interposed between the linear segments of the center conductor. The ferrite slabs 14, 15 in FIGS. 4 and 5, are slotted to receive the vanes which extend between the ground plane plates 16, 17. In the simpler structure of FIGS. 2 and 3, ground plane plates 1 and 2 are electrically connected together as by shorting screws or some other electrical short circuiting means. In the structure of FIGS. 4 and 5, the conductive vanes electrically connect the ground planes and act as shields to decouple the center conductor line segments from each other.

Close spacing of the segments of the folded center conductor is aided by the high dielectric constant of the ferrite medium. Proximity of the line segments permits a reduction in the physical size of the phase shifter without a loss in electrical length and reduces the drive power required for the solenoid as the solenoid can have a smaller internal diameter and therefore have its magnetic field more tightly coupled to the ferrite disposed within the solenoid.

A strip transmission line in which wave propagation occurs through air is customarily referred to as "air filled" whereas a strip transmission line in which wave propagation occurs in a ferrite medium is customarily termed "ferrite loaded."

The characteristic impedance of an air filled strip transmission line is given by the following simplified expression:

$$Z = 138 \log \frac{8b}{\pi w}$$

where

Z is the characteristic impedance of the air filled strip transmission line

b is the ground plane spacing

w is the width of the center conductor.

The expression is valid provided the thickness of the center conductor is small in comparison with the ground plane spacing.

The relation between the characteristic impedance of an air filled strip transmission line and a ferrite loaded structure is given by the expression

$$Z = Z_0 \sqrt{\frac{\epsilon_1}{\mu_1}}$$

where

Z_0 is the characteristic impedance of the ferrite filled strip transmission line

ϵ_1 is the relative dielectric constant of the ferrite medium

μ_1 is the relative permeability of the ferrite medium.

As is known, the propagation factor γ of a transmission line is expressed in terms of attenuation α and phase shift β , thus

$$\gamma = \alpha + j\beta$$

For any frequency ω above the cut-off frequency ω_c , in a strip transmission line, the attenuation $\alpha = 0$ and

$$\beta = \omega \sqrt{\mu \epsilon} \sqrt{1 - \left(\frac{\omega_c}{\omega}\right)^2}$$

Where the operational frequency ω is well above cutoff, viz., $\omega > \omega_c$

$$\beta \approx \omega \sqrt{\mu \epsilon}$$

In a ferrite loaded strip transmission line operated at a frequency that is well above cutoff, the dielectric constant ϵ of the ferrite is fixed whereas its permeability μ_1 is influenced by an applied magnetic field. Therefore, at the operational frequency, phase shift β is proportional to $\sqrt{\mu}$ and as μ is controlled by the applied magnetic field, the phase shift β is controllable.

When using the invention, the intensity of the magnetic field can be adjusted to place the operating region of the ferrite either above or below resonance. In most applications where high power signals are involved, it is preferable to have the operating region above resonance.

Modifications of the embodiments of the invention depicted in the drawings may be made without departing from the essential concept of the invention and, indeed, are apparent to those skilled in the electronics art. It is intended, therefore, that the invention not be limited to the precise arrangements illustrated, but rather that the invention's scope be construed as delimited by the appended claims.

What is claimed is:

1. Apparatus for shifting the phase of an electrical signal comprising:

a strip transmission line having its center conductor disposed between spaced ground plane plates;

a pair of ferrite slabs disposed between the ground plane plates;

the center conductor of the strip transmission line having folds situated between the pair of ferrite slabs whereby wave propagation along the folded portion of the line occurs in the ferrite medium;

and means for establishing a magnetic field to which the ferrite slabs are subject for controlling wave propagation in the ferrite medium.

2. Apparatus for shifting the phase of an electrical signal, the apparatus comprising:

a strip transmission line having its center conductor disposed between spaced ground plane plates;

a pair of ferrite slabs disposed between the ground plane plates;

the center conductor of the strip transmission line having folds situated between the pair of ferrite slabs whereby wave propagation along the entire folded portion of the line occurs in the ferrite medium, the folds having spaced parallel segments connected by 180° bends;

and means for establishing a magnetic field to which the ferrite slabs are subject for controlling the phase of a signal propagating along the strip transmission line.

3. Apparatus for shifting the phase of an electrical signal, the apparatus comprising:

a strip transmission line having its center conductor disposed between spaced ground plane plates;

5

ferrite slabs disposed between the ground plane plates; the center conductor of the strip transmission line being folded between the ferrite slabs whereby wave propagation along the entire folded portion of the line occurs in the ferrite medium;

electrically conductive members interposed between folded segments of the center conductor, the electrically conductive members interaction between adjacent segments of the center conductor;

and means for establishing a magnetic field to which the ferrite slabs are subject for controlling wave propagation in the ferrite medium.

4. Apparatus for shifting the phase of an electrical signal, the apparatus comprising:

a strip transmission line having its center conductor interposed between spaced ground plane plates;

ferrite slabs disposed between the ground plane plates; the center conductor of the strip transmission line being

folded between the ferrite slabs whereby wave propagation along the entire folded portion of the line occurs in the ferrite medium, the folded center conductor having spaced parallel segments;

electrically conductive vanes interposed between ad-

6

jacent segments of the center conductor, the vanes extending between and abutting the ground plane plates whereby to reduce interaction between adjacent segments of the center conductor;

and means for establishing a magnetic field to which the ferrite slabs are subject for controlling wave propagation in the ferrite medium.

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